Energetics of Walking With a Robotic Knee Exoskeleton

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The authors tested 4 young healthy subjects walking with a powered knee exoskeleton to determine if it could reduce the metabolic cost of locomotion. Subjects walked with a backpack loaded and unloaded, on a treadmill with inclinations of 0° and 15°, and outdoors with varied natural terrain. Participants walked at a self-selected speed (average 1.0 m/s) for all conditions, except incline treadmill walking (average 0.5 m/s). The authors hypothesized that the knee exoskeleton would reduce the metabolic cost of walking uphill and with a load compared with walking without the exoskeleton. The knee exoskeleton reduced metabolic cost by 4.2% in the 15° incline with the backpack load. All other conditions had an increase in metabolic cost when using the knee exoskeleton compared with not using the exoskeleton. There was more variation in metabolic cost over the outdoor walking course with the knee exoskeleton than without it. Our findings indicate that powered assistance at the knee is more likely to decrease the metabolic cost of walking in uphill conditions and during loaded walking rather than in level conditions without a backpack load. Differences in positive mechanical work demand at the knee for varying conditions may explain the differences in metabolic benefit from the exoskeleton.

Keywords: locomotion, robotics, biomechanics, assistance, terrain

One goal for developing robotic lower limb exoskeletons is human performance augmentation. Robotic exoskeletons that can enhance the performance of able-bodied humans serving as firefighters, military personnel, and/or construction workers could reduce injuries and improve worker efficiency. To be successful in these environments, robotic devices must be suited to the task specificity of the demands. Many robotic exoskeletons that have been described or studied in the scientific literature have been evaluated based on their ability to reduce the metabolic cost of walking and/or running, because walking and/or running is usually one component of the user's likely tasks.¹⁻⁴ If a robotic exoskeleton can reduce the metabolic energy expenditure during locomotion at a constant speed, the device could make it easier for users to accomplish their goals with less physical exertion. So far, few exoskeletons have managed to reduce the metabolic cost of walking compared with able-body, unassisted walking.^{1,5} Major obstacles to reducing metabolic cost with exoskeletons are weight, portability, power supply, and transmission of exoskeleton power to the biological joints.

Uphill walking, load carriage during walking, and walking over varied terrain are locomotion tasks that are important for many robotic lower limb exoskeletons intended for human performance augmentation. Firefighters and military personnel are often required to carry loads in excess of 30 kg, and both may cover a range of

natural terrain, including steep inclines.⁶⁻⁸ The metabolic cost of walking with a load increases linearly with load, and the metabolic cost of uphill walking is greater than that of level walking.⁹⁻¹² In some circumstances, the addition of a heavy backpack load and an incline can more than double the metabolic cost of walking relative to unloaded walking on level ground at the same speed. The type of terrain is also a determinant of metabolic cost. Walking on smooth surfaces, like floors or roads, requires less energy than walking on uneven surfaces, like dirt, gravel, or sand.^{13,14}

From a biomechanical perspective, an exoskeleton that assists at one lower limb joint but not others should alter energetic cost differently depending on the locomotor task. A large majority of the total mechanical work performed by muscles during a step can be calculated as the summation of positive and negative mechanical work at the ankle, knee, and hip. This assumption does not include work performed by motion of soft tissues or include work done at the toe, vertebral, and other joints.^{15,16} Recent studies have found that including translational work of segments is able to more accurately capture the total work of a step and that the work performed by the hip and knee joints may be underrepresented in traditional inverse dynamics.¹⁷ However, studies using traditional inverse dynamics to calculate positive and negative mechanical work at the hip, knee, and ankle suggest that there are different metabolic costs associated with muscular work performed about these joints. The results from these studies have allowed an energetic efficiency to be associated with the work done at each joint. Work at the ankle has the highest apparent efficiency, followed by the knee and then the hip.¹⁸⁻²⁰ During level walking, the metabolic demand associated with work done about the knee is low, because it has relatively low amounts of positive work, and it is likely that the negative work about the knee is not metabolically demanding.^{18,19} However, during uphill and loaded walking, there is more positive mechanical work done at the knee than during level walking.^{21,22} A robotic exoskeleton that assists at the knee joint is likely to have a better chance of reducing metabolic energy expenditure during uphill and loaded walking than during level walking.

Some exoskeletons have had success in reducing the metabolic cost of walking up inclines or with heavy loads. A soft exosuit

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was shown by Panizzolo et al²³ to decrease the metabolic cost of walking with a load equivalent to 30% body mass. The suit provided ankle plantar flexion, hip flexion, and hip extension moments. The authors note that there may have been unquantified actuation provided at the knee joint by a multiarticular actuator. In a study by Mooney et al,¹ an ankle exoskeleton that provided plantar flexion torque during push off was found to reduce the metabolic cost of walking with a 23-kg load. Another ankle exoskeleton with plantar flexion assistance was able to increase the maximum weight carried before reaching fatigue walking uphill.²⁴ Two studies have found that walking uphill with an ankle exoskeleton that provides plantar flexion assistance was more energetically efficient than walking with the exoskeleton unpowered.^{25,26} A hip exoskeleton that provides mainly flexion torque was able to reduce the metabolic cost of walking on an incline of up to a 10% grade compared with normal shod walking.²⁷ This hip exoskeleton and a quasi-passive exoskeleton were both able to reduce the metabolic cost of level walking.^{5,28}

The long-term goal of most exoskeletons is to be used in real-world applications, but the vast majority of studies to date have examined exoskeletons in highly controlled laboratory settings. There are many advantages to testing in laboratory settings, but one disadvantage is the lack of variability and complexity in the ambulatory tasks. Walking at a single speed on a treadmill is a good way of collecting data for a steady-state condition, but there are very few steady-state conditions in real-world ambulation. Walking in the real world is often over uneven and varied terrain, interspersed with transitions to different speeds and changes in direction. It would be useful to have a method of evaluating exoskeletons in nonsteady-state, real-world environments.

The main purpose of this study was to evaluate potential metabolic savings from wearing a prototype robotic knee exoskeleton during walking. The prototype knee exoskeleton aims to assist healthy, physically intact users in performing intense locomotor tasks.²⁹ Walking uphill and walking with a load are 2 specific locomotor tasks that the exoskeleton is designed to assist with. Based on the apparent metabolic efficiencies of work done at the joints and the mechanical work contributions of the lower limb joints, we hypothesized that the knee exoskeleton would reduce the metabolic cost of walking on the level with a load, up an incline

without a load, and on an incline with a load compared with walking without the exoskeleton. Further, we hypothesized that the exoskeleton would not provide metabolic benefit for level walking without load. To evaluate this hypothesis, we had subjects walk on a treadmill in a laboratory under different loads and incline levels while we measured metabolic energy expenditure. A secondary goal of this study was to determine if measuring metabolic energy expenditure while subjects walked in an outdoor setting across changing terrain and gradients provided additional insight into the potential benefit of the robotic knee exoskeleton.

Methods

We recruited 4 healthy male participants (mean [SD]; 29.6 [3.8] y, 85.8 [16.4] kg). We screened potential participants by testing for adequate fit of the knee exoskeleton (Knee Stress Release Device™, B-Temia Inc, Canada) to each participant (Figure 1). The powered knee exoskeleton assisted at both knee joints and throughout the gait cycle by providing both positive power and resisting joint extension. The device had a maximum torque output of 60 N·m, a maximum angular velocity of 720°/s, a maximum angular acceleration of 720 rad/s/s, and a maximum angular power output of 120 W. The controller for the exoskeleton was a state machine that used intrinsic sensing and acted as a virtual spring. The exoskeleton was able to provide assistance during stance and during swing, both in positive work and in negative work. The device did not output a torque or power metric, so it is not possible to determine how each individual user relied on the exoskeleton for negative or positive work. The controller had 7 tunable parameters for each leg and one parameter common to both legs (Table 1). The controller could be adjusted by the participant to provide 0%–100% of chosen assistance parameters. The Institutional Review Board of the University of Michigan approved the study protocol, and all participants gave informed consent. All users completed a minimum of 4 hours of training over 2 or more days and at least one day in advance of data collection. We began training sessions by adjusting the mechanical fittings of the knee exoskeleton to the user. The physical interface between human and machine included a waist belt, hard thigh and shin cuffs with soft straps, and a soft material loop around the shoe. Next, we tuned the controller parameters using the participant's

Figure 1 — A subject on the treadmill in the laboratory for the level walking, incline walking, and outside the laboratory for the outdoor testing. The participant is wearing a respiratory measurement system and the knee exoskeleton in all images.

Table 1 Tuning Parameters

Tunable parameter	Parameter range	Left and right leg tuning
Maximum flexion assistance provided in swing phase	0°–20 N·m	Independent
Maximum extension assistance provided in swing phase	0°–20 N·m	Independent
Maximum eccentric control provided during weight bearing	15°–60 N·m	Independent
Maximum extension assistance provided during weight bearing	15°–60 N·m	Independent
Knee angle at which flexion assistance ends in swing phase	40°–60°	Independent
Knee angle at which extension assistance ends in swing phase	20°–40°	Independent
Rate at which assistance changes	1–10 level	Common
Correction for persistent torque in free mode		Independent

Note: The parameters were tuned for each participant. Most parameters could be tuned on the left and right leg independently, whereas one parameter was tuned common to both legs.

feedback while they performed different ambulatory tasks. The tasks included walking on a treadmill, walking around the laboratory space, and walking through an outdoor area with grass and sloped ground. We requested user feedback on the comfort of the device in order to adjust the fit. To assist with tuning the exoskeleton, we changed one parameter at a time and asked the user which condition they preferred. We used the controller's tunable parameters to adjust the assistance profile for each leg and set the assistance level to 100%. The device had kinematic sensors at the ankle, knee, and hip joints, but only provided mechanical assistance at the knee joint. The exoskeleton did not transfer any weight to the ground, but interacted with the thigh and shank to provide mechanical assistance. The motor at the knee joint was connected to the thigh and shin cuffs by a metal bar. Subjects carried the battery (~2.5 kg) for the exoskeleton in a small, lightweight backpack (Figure 1). The total mass of the exoskeleton, including the battery, was 8.4 kg.

Participants completed 12 ambulatory tasks over the course of 2 days of data collection. They wore a facemask (CareFusion Oxycon Mobile, Hoechberg, Germany) to record respiratory measurements. At the start of each session, participants stood at rest for 6 minutes while we recorded metabolic measurements. The 12 ambulatory tasks included walking in 4 different conditions on 3 surfaces: a level treadmill, a treadmill inclined at 15°, and a 1.1-km outdoor course of varied terrain and gradients (Figure 2). For the treadmill trials, participants walked for 6 minutes or longer if needed in order to ensure that respiratory measurements stabilized. After finishing the outdoor course, participants stood for 6 minutes in order for their metabolic measurements to return to resting levels.

The 4 conditions were: (1) without the knee exoskeleton and without backpack load, (2) with the knee exoskeleton and without backpack load, (3) without the knee exoskeleton and with an 18.1-kg backpack load, and (4) with the knee exoskeleton and with an 18.1-kg backpack load. The order of the trials was pseudo-randomized such that all of the indoor testing was done before the outdoor testing and the number of times participants needed to don the knee exoskeleton was minimized. After each trial, participants were given water and allowed to rest for as long as they needed.

Level walking and outdoor walking were done at the participants' preferred speed, using the same speed for both conditions. The preferred speed was determined by asking participants, as they walked with the knee exoskeleton on the level treadmill at varying speeds, whether it was too slow or too fast until the subject did not want the speed altered. To ensure that participants walked at the preferred speed on the outdoor course, a pacesetter walked in front of the subjects, timing their walking with a metronome and course

Figure 2 — Topographical data of outdoor course. The contour lines indicate elevation changes of 1 ft (30.5 cm). The 1.1-km trial is outlined in black. The participants started at the bottom left, went to the end of path, and then followed the loop back around to where they started.

markers at 8 m intervals. We recorded the total time to complete the outdoor course for each subject in each condition. For the laboratory inclined-treadmill condition, participants walked at half of their preferred speed from the level treadmill trials. This was done to ensure that subjects could complete the incline-with-backpack-load condition while maintaining a respiratory exchange ratio <1.0. A respiratory exchange ratio lower than one implies that metabolic energy is being provided by aerobic metabolism, suggesting that the metabolism measured by gases at the mouth is reflective of the metabolism at tissue level. We based this decision on pilot tests prior to the first experiment.

Data processing was carried out as follows. We calculated metabolic cost (W/kg) using $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ measurements and the Brockway equation.³⁰ We subtracted the metabolic cost of standing at rest and divided the metabolic cost by the participant's body mass (unadjusted for the extra mass associated with the load of the backpack and/or exoskeleton). For resting and treadmill trials, we calculated the mean of the final 3 minutes of data to find the average cost. We averaged metabolic cost across participants and used planned paired *t* tests with Bonferroni corrections to determine whether the knee exoskeleton had an effect on the metabolic cost in each of the 4 indoor conditions.

Because a steady state was not achievable in the outdoor course, we averaged the outdoor metabolic data over 5-second

intervals to provide a time series of metabolic cost values. The outdoor metabolic cost data were filtered with a fourth-order, low-pass, Butterworth filter (cutoff frequency of 0.0078 Hz). We determined the cutoff frequency by using residual analysis for all trials, with equal weight on reduced signal distortion and noise, and then found the average value.³¹ We then normalized the data to the percent of time taken to complete the course and averaged the data across participants for 0% to 125% of time taken to complete the course. We included the data from 100% to 125% of course completion time in order to make sure we had the time at which the participants returned to steady state.

We calculated the gradient of the outdoor course over 5-second intervals for each trial using the time to complete the trial and topographical data with an elevation resolution of 1 ft (30.5 cm).³² To find the time delay between gradient and metabolic cost, we filtered the data using the same filter used for the outdoor metabolic cost and then performed a cross-correlation between the gradient and the metabolic cost data for each trial. The maximum possible time delay was set to 3 minutes, because studies have suggested that the time lag is often around 1 minute.³³

Results

Subjects' preferred walking speed on the level treadmill condition was 1.0 (0.1) m/s (mean [SD]). All subjects were able to maintain this speed on the outdoor course with active feedback from the experiment team.

The knee exoskeleton had the greatest effect in the uphill condition with the backpack load (Figure 3), but we observed substantial variability in metabolic cost between subjects. All 4 subjects had less metabolic energy expenditure using the knee exoskeleton when walking up the inclined treadmill with the backpack compared with not using the exoskeleton. The mean decrease between the 2 conditions was 4.2% (pairwise *t* tests with Bonferroni correction $P = .01$). We found no other statistical differences between the knee-exoskeleton and no-knee-exoskeleton conditions for the indoor trials.

Change in metabolic cost with exoskeleton

Figure 3 — The individual and the average percentage difference in metabolic cost when using the knee exoskeleton. The bars represent individual participant data. The circle indicates the mean for that condition, with error bars of ± 1 SD. *Significant effect of the exoskeleton on metabolic cost. A negative value indicates that walking with the knee exoskeleton resulted in lower metabolic cost than walking without the knee exoskeleton.

Figure 4 — Average metabolic cost during the outdoor trials. Data were averaged over 5-second periods and filtered with a fourth-order low-pass Butterworth filter (cutoff frequency of 0.0078 Hz). Bands represent the 95% confidence intervals. (A) Walking without loaded backpack, and (B) walking with loaded backpack.

Figure 5 — Example data from one subject showing the terrain gradient and metabolic cost across time. Visual inspection showed that the peaks in metabolic cost occurred roughly a minute after the peaks in gradient.

Results indicated that the average metabolic cost for outdoor walking without the knee exoskeleton was less than for walking with the knee exoskeleton for both the unloaded and the loaded trials (Figure 4). The subjects did not reach steady-state conditions during the outdoor tests. The 95% confidence interval for average metabolic cost was wider with the knee exoskeleton than without the knee exoskeleton. The correlation between the gradient and the metabolic cost was small ($R^2 = .047$), with an average time lag across subjects of 5 seconds. The average of data time series showed similar patterns, with peaks of metabolic energy expenditure data occurring after the peaks of the gradient data. Figure 5 shows correlation data from one subject in the no-exoskeleton, no-load condition as an example.

Discussion

The knee exoskeleton provided energetic benefits to users during loaded walking uphill. The decrease in energetic cost was relatively small ($\sim 4.2\%$); however, it was equivalent in metabolic power to removing a load of 3.7% of body weight (3.2 [0.6] kg, mean [SD])

from a backpack during walking (Figure 3).³⁴ The knee exoskeleton did not output information about exoskeleton work or torque during walking, but we know that the exoskeleton provided both assistive positive torque and resistive torque. Knee mechanical work increases as a percentage of the total mechanical work of walking with increasing load and increasing incline gradient.^{21,22,35} Although studies by Huang and Kuo²¹ and McIntosh et al²² used different walking speeds, the data suggest that incline walking requires increased positive work at the knee for a larger percentage of stride than loaded walking. The knee exoskeleton was beneficial in the condition which required the most knee positive work. We believe that the knee exoskeleton did not provide a benefit in the other conditions because of the small positive mechanical work requirements at the knee and the increased metabolic cost associated with the mass of the exoskeleton. From these results, we suggest that the knee exoskeleton could provide a reduction in metabolic cost at greater inclines and with heavier loads.

Although we did not statistically analyze the energetic cost data from the outdoor walking conditions, it seems clear that the knee exoskeleton did not result in lower metabolic cost compared with walking without the exoskeleton for either unloaded or loaded conditions (Figure 4). The difference in metabolic cost between using and not using the knee exoskeleton was less in the loaded conditions than the unloaded conditions. Because loaded walking requires greater knee positive mechanical work than unloaded walking, the exoskeleton may have been less detrimental in the loaded condition because it assisted with the increase in positive work demand at the knee. It is possible that the changing gradient of the outdoor course could have made it harder for the control system of the knee exoskeleton to predict and provide the most beneficial power throughout the course. As participants walked over different terrains, they may have frequently adapted their gait and possibly their reliance on or interaction with the knee exoskeleton. This means that the knee exoskeleton would have had to adjust repeatedly to different gait patterns for optimal performance. Without continuous metrics for exoskeleton torque, power, and displacement, it is not clear how well the exoskeleton controller adjusted to changing terrain conditions.

Because of the nature of the outdoor testing course, the participants did not reach a metabolic steady state. Averaging the metabolic data every 5 seconds provided useful insight into the metabolic cost throughout the task, but it did not take into account delays in metabolic expenditure dynamics and time lags.³³ Although we used a pacemaker to maintain a steady speed, it is possible that there were small fluctuations in speed. As such, the normalized data for each participant were accurate in terms of time to complete the course, but may have had slight discrepancies in absolute position on the course. Another limitation of the outdoor data was that one of the customary requirements for energetic cost analysis with spirometry was not met. The respiratory exchange ratio sometimes exceeded the value of 1 during the outdoor course trials. A respiratory exchange ratio >1 indicated that anaerobic metabolism was likely contributing to muscle work but was not being factored into the energetic cost analysis based on oxygen consumption. This could have resulted in an inaccurate estimation of the metabolic cost of walking. For all trials, the respiratory exchange ratio did not often exceed 1 and very rarely exceeded 1.1. Given that subjects walked the same outdoor path for loaded and unloaded conditions, both with and without the exoskeleton, it does not seem likely that the anaerobic energy expenditure skewed the results between the 4 outdoor conditions.

For both indoor and outdoor conditions, the efficacy of the knee exoskeleton in reducing metabolic cost was highly variable between subjects and across conditions (Figure 3). For example, participant 4 saw a decrease in metabolic cost with the knee exoskeleton in 3 out of 4 indoor conditions, whereas participants 2 and 3 saw only an energetic benefit in 1 indoor condition. In the outdoor conditions, the confidence interval was greater for the knee-exoskeleton trials than the no-knee-exoskeleton trials, especially in the loaded conditions.

We believe that the intersubject variability may have been due to the quality of the fit, the participant's skill with the device, the tuning of the device, and the participant's level of fatigue. Participants 1 and 4 had thicker thighs and calves than participants 2 and 3, which may have resulted in a better fit. Although the testing protocol included at least 4 hours of training with the device for all inexperienced users, this may not have been enough practice for proficiency in using the knee exoskeleton. We noticed that some participants were able to adapt their walking style to better incorporate the assistance of the device than others were. Participant 4, for example, seemed to relax into the device and provide the minimum input required for the knee exoskeleton to move his legs for him. Other participants appeared to walk as they would without the device, doing most of the work themselves. Moreover, during training, the participants tried varying assistance levels for the purpose of tuning the device.

We tuned the device using the user's feedback rather than quantitative data for each task. The use of qualitative feedback means that we may not have set the device to the energetically optimum parameters. As inexperienced users, the participants may have had trouble interpreting how the changing parameters affected their gait and whether the changes were beneficial or detrimental. More participant training time may have resulted in a more energetically optimal configuration of the device. However, the ability to measure metabolic cost in real time would be invaluable for achieving optimal tuning of the device. This is not currently possible, but techniques are in development.^{36,37}

To minimize the effect of fatigue across participants, we pseudo-randomized the order of the trials. However, some testing sessions were very long and the participants were required to fast throughout, which could have affected the metabolic data of the later trials. Testing the resting metabolic power before each trial may have helped mitigate this issue, but would also have increased testing and fasting time for the participants.

We anticipated that the correlation between the gradient and the metabolic cost would produce a time lag of roughly 1 minute based on previously published research.³³ This was in stark contrast to the calculated result of a 5-second delay between the gradient and the metabolic cost using time series correlation. The average R^2 value showed that the best correlation accounted for only 4.7% of the variation in the data. We visually inspected the metabolic cost overlaid with the gradient data for all trials and found that the peaks in the gradient data occurred roughly a minute before the peaks in metabolic cost, which is in agreement with data from Koller et al.³³ It may be that the inherent nonlinear relationship between gradient and metabolic energy expenditure prevented the linear correlation from providing an accurate assessment of the time lag.

In the knee exoskeleton no-load trials, participants carried an approximately 2.3-kg battery in a small backpack. We considered the battery to be part of the knee exoskeleton, and in the loaded trials, we added the battery to the large 15.8-kg backpack. To compare across loaded trials, we kept the weight in the backpack for the no-knee-exoskeleton trials at 18.1 kg. We did not add extra mass in the

unloaded no-exoskeleton conditions to match the mass associated with wearing the exoskeleton, because we wanted to evaluate if wearing the exoskeleton provided a metabolic benefit over unaided walking. A final limitation of this study was the small number of participants. More subjects would have produced better statistical interpretations, but this was not possible within the time constraints of this study. However, having some data available on the energetics of loaded and unloaded walking allows for better planning of future studies that will be able to recruit a larger subject population.

To conclude, the knee exoskeleton reduced metabolic cost when walking at a 15° incline at 1 (0.1) m/s with a 15.8-kg load and 2.3-kg battery. There was large intersubject variability in the other indoor conditions, but, overall, these conditions did not demonstrate a metabolic benefit from wearing the knee exoskeleton. These results suggest that a knee exoskeleton can reduce metabolic cost in situations in which greater positive mechanical work is required at the knee. They also demonstrate the difficulty of translating treadmill-based laboratory tests to real-world outdoor conditions.

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